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Development of Proximity and Electrostatically Focused Diodes for UV Measurements From Sounding Rockets

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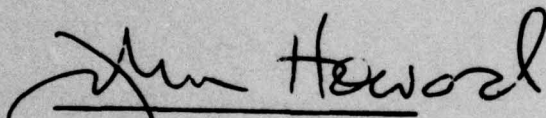


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20. Abstract (Continued)

spectrograph. The problems associated with construction of these devices are discussed. Laboratory test results demonstrating the use of these tubes are given.

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Preface

The work described herein was performed in part under contract to the Air Force Geophysics Laboratory. Professor C. M. Cooke of the Massachusetts Institute of Technology was responsible for the invaluable electrical field analyses and resulting design changes. Dr. W. Stuckey performed the ion microprobe mass analysis at Aerospace Corporation. The digicons were designed and fabricated at Electronic Vision Company, at which the contributions of Mr. H. Alting-Mees are specifically noted. Significant contributions were made by consultants drawn from other organizations within Martin Marietta, namely the corporation's laboratories in Baltimore, who performed Auger and other analyses, and the Orlando Division of the Aerospace Group, who redesigned and fabricated the diode arrays.

This work is a part of the AFGL Multispectral Measurements Program (MSMP).

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Development of Proximity and Electrostatically Focused Diodes for UV Measurements From Sounding Rockets

1. INTRODUCTION

The digital multichannel photometer (DMP) or digicon was first described by Beaver and McIlwain.¹ Subsequent developments and applications were presented at the previous two Photoelectronic Image Devices Symposia.²⁻⁴ More recent developments and applications were surveyed by Choisser in 1977.⁵ Much of the referenced work describes detectors used in ground based astronomy where size, weight, power and ruggedness were not of great significance. Our application, which required the detector to be mounted in a number of small rocket borne instruments, therefore necessitated considerable additional development.

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2. CHOICE OF DIGICON

The choice of detector for this application was dictated by the key requirements of: (a) photon counting sensitivity, (b) 50 percent minimum counting efficiency, and (c) up to 50,000 counts/sec/pixel.

Other requirements which played a part included the field of view and packaging constraints.

Image intensifiers with phosphor outputs optically coupled to self-scanned photodiode arrays were considered. It proved very difficult to optically couple the image on the phosphor to the diode array. If an optical train were used, light losses were too high to permit photon counting. If the photodiode were to be in direct contact with the phosphor, then it was difficult to satisfy field of view requirements without substantial added complexity. The self-scanned arrays, moreover, have difficulty with counting efficiency, since there is considerable dead area on the array. Another problem is the low clock rate which does not allow a short enough frame time at high count rates.

Another concept considered was to seal a microchannel plate intensifier in a tube with a segmented multiple anode. In this concept, adequate electronic gain is provided by the intensifier, a custom designed anode would satisfy field of view requirements, and multiple feedthroughs would permit coupling the anode array to charge amplifiers. Vendor responses indicated an inability to satisfy the count rate due to limited conductivity in the channel plate pores. It also appeared to be marginal in the area of counting efficiency. Finally, the notion of operating channel plates in sealed tubes was novel at the time and it was clear that serious reliability problems existed. Restrictions on the applied voltage meant that sealed units would be operating at reduced gain, below the level of pulse saturation, with the attendant increased susceptibility to tube bias variations and ripple and degraded pulse height distribution.

Only slight consideration was given to beam scanned type detectors with enough intensification for photon counting. The size, weight, power and general complexity of this approach seemed totally inappropriate for a compact sounding rocket instrument.

The digicon approach offered the chance to meet all of the requirements. It permits simultaneous photon counting in all channels, it can handle high count rates, it has high efficiency, its data format can be easily matched to the field of view, and its pulse height distribution is superior to that of electron multipliers.

The use of the digicon required complementary technologies, namely, semiconductor technology, dense electronic packaging and development of low-noise charge amplifiers which largely overcome the digicon disadvantage of relatively low gain.

3. PERFORMANCE AND DESIGN REQUIREMENTS

The digicon detector subsystem was to detect photons at wavelengths extending from 1200 Å - 3000 Å. One type of detector would be used in a spectrometer which would resolve this spectral region into 50 Å elements. Therefore the digicon would use a linear silicon diode array of 36 elements, a magnesium fluoride window and a cesium telluride photocathode. The other type of detector would use a 10 × 10 element silicon diode array to obtain spatial resolution. This detector would cover selected portions of the same spectral region determined by the type of window and photocathode used; namely cesium iodide photocathodes on either sapphire (Al_2O_3) or magnesium fluoride windows and cesium telluride photocathodes on sapphire windows. Additionally, several interference filters mounted on a wheel within each instrument would further define the spectral bandpass.

The primary requirements levied on both types of detectors include:

- (a) High quantum efficiency, 7 percent minimum at the transmission peak;
- (b) Gain sufficient for counting each photoelectron;
- (c) Photoelectron counting efficiency of at least 50 percent;
- (d) Less than 1 percent counting dead-time;
- (e) Dark count rate less than 1 count per second for each element;
- (f) Linear response from 1 to 5×10^4 cps.

Of these requirements, the design drivers were photoelectron counting, gain, and a counting efficiency of at least 50 percent.

4. ORIGINAL DESIGN CONCEPTS

As originally conceived, both detector types would be electrostatically focused and avoid the weight, power and space associated with magnetic focusing. Overall mounted digicon dimensions (including the encapsulant and housing) not to exceed 8 cm diameter and 8 cm length were desirable to fit within the folded optics of the instruments with reasonable obscuration and appeared practical for fabrication. Because electrostatically focused tubes with plane photocathodes have severe off-axis distortion, a field mesh just beyond the photocathode was considered to improve the performance by creating a virtual electron image of the cathode more compatible with the needs of the focusing electron optics.

5. DEVELOPMENT MODIFICATIONS

The electrostatically focused digicons produced a more severely curved electron image plane than was compatible with the optical design and resolution requirements of the two types of instruments. This was determined fairly early in the program as the overall instrument system design progressed. The suggested approaches to solving this curvature problem differed for the two detectors. For the 10×10 tube the only practical choice was to change to proximity focusing. An overall mounted digicon length of 4.5 cm was selected. For the 1×36 tube the only practical approach was to use a faceplate with the photocathode surface curved ($R = 13$ cm) to match the Petzval curvature of the spectrometer. The electron optics then dictated that the electrostatically focused tube would have to be lengthened to approximately 10 cm and have a 1:2/3 demagnification.

Other significant requirements which were defined early in the program were the use of a corona discharge grid on the outer surface of the faceplate with at least 0.85 transmission, operating bias of 25 kV, and specifications on materials, quantum efficiency, gain, pulse height distribution, dark count, uniformity and environments.

Some of these are summarized on Table 1.

Table 1. Key Digicon Specifications

Quantum Efficiency at Peak:	≥ 0.07 , CsTe on Al_2O_3 ≥ 0.07 , CsI on Al_2O_3 ≥ 0.16 , CsI on MgF_2
Gain at 25 kV:	6000, equivalent to a charge pulse of 9.6×10^{-16} coulomb
Pulse Height Distribution:	FWHM of 3.5 Kev when measured with electronics of equivalent FWHM
Dark Count Rate:	0.5 per second per element
Uniformity:	PHD peaks within ± 5 percent pixel to pixel
Resolution:	Electron optical circle of confusion of 0.5 mm or less
Dark Current	< 2 na at 25 C per element

The 1×36 diode array was specified at a length of 2.74 cm and height of 0.17 cm with each element 0.057 cm wide except for the 3 elements closest to Lyman alpha which were half the width. Diode spacing was 0.073 cm on centers.

The 10×10 array used 0.107 cm square elements spaced 0.127 cm on center. The monolithic silicon array was to be bonded to an alumina substrate using gold-silicon eutectic preform. The electrical requirements of the arrays were also specified. This included diode capacitance, leakage, crosstalk, trace resistance, reverse voltage breakdown and operation, forward voltage drop and defect tolerance.

6. DESIGN AND FABRICATION PROBLEMS

During the fabrication of the detectors two major problem areas arose. The first was the poor performance of the diode arrays. The major effect was greatly increased noise in the digicon. This was attributed to the use of silicon with bulk-resistivity of 10 ohm cm or less instead of 100 ohm cm or greater, poor layout of the traces resulting in high capacitance, and some defects in the diode processing. The diode arrays which had originally been designed and developed by an outside vendor were redesigned completely to eliminate the deficiencies noted. In addition, the occurrence of a weak intermetallic region between the gold pad on the chip and the aluminum wire was prevented by using a metal bridge containing titanium between the gold and aluminum which did not form the weak intermetallic (or "purple plague") when exposed to the digicon processing temperatures.

The second problem was the inability of the proximity focused digicon to operate at the rated bias of 25 kV. High voltage breakdown was at first believed to be initiated by field-emission but this was not supported by conclusive evidence. After an extensive review of the observed phenomena, nine possible causes for the failures were presented. After the potential causes were checked out one by one, a second review was conducted to evaluate the findings. The four changes suggested at that time were intended to reduce the electrical field stresses generally and at local regions of the digicon tube. The tube body was increased from 1 to 2 cm in length (an earlier analysis having shown that this would have only a modest effect on system MTF which was dominated by diode element size). The shape of the cathode flange was changed. The anode flange was extended inside the tube body. The metallized region of the tube body (which facilitates brazing of flanges) was also modified. The changes to the electrical field can be seen in Figures 1 and 2 which show the percentage stress in the original and modified configurations. Figure 3 shows a cross-section of mounted digicon sensor with these modifications. Although the basic tube body increased by 1 cm, the mounted sensor did not grow in height from 4.5 cm overall because of a generous recess of the tube inside the housing to permit the housing to be firmly attached to strong

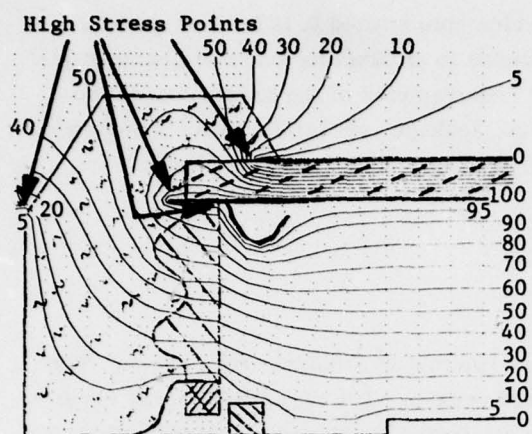


Figure 1. Original Configuration of Proximity-Focused Digicon

Figure 2. Final Configuration of Proximity-Focused Digicon

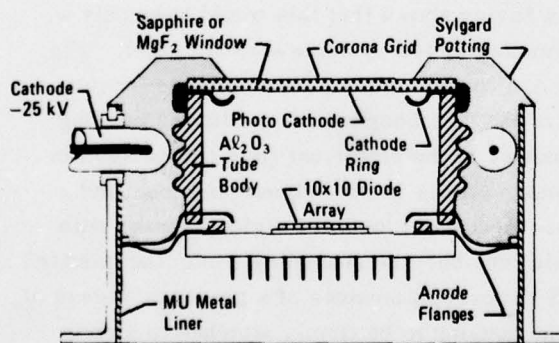
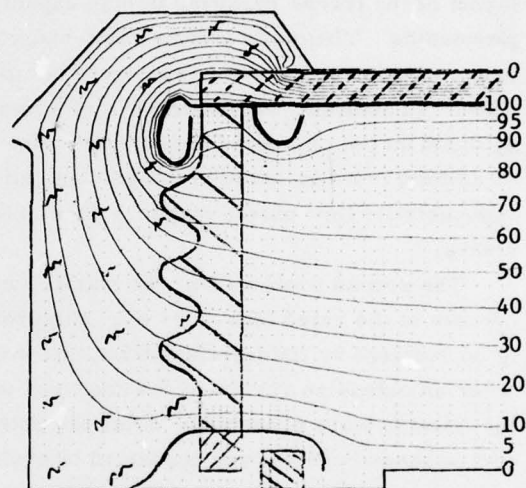


Figure 3. Cross Section of Digicon Sensor

points in the instrument. Another small change was the termination of the anti-corona grid. Initially it was via a single wire to the housing ground. This was considered to be undesirable as a reliability risk and a high electrical stress point. This was first suspected when faint flashes were detected from the surface of the Sylgard encapsulant. Computer analyses of the field considering the detector and adjacent optical elements confirmed the high stress. The connection of the grid was, therefore, made with a conductive rubber (Ablestik) applied completely over the Sylgard potting and flowed onto the outer gold ring of the faceplate grid and over the tube housing to obtain good electrical contact. The low outgassing of this material was verified by total gas analysis. The same material was also used to suppress discharges at the point where the high voltage cable passes through the tube housing. These changes eliminated the high voltage breakdown problems of our proximity focused digicons. These units have demonstrated the ability to withstand up to 35 kV.

7. PROCESSING DIFFICULTIES

Another development problem was encountered after the first digicon with the aforementioned modifications was processed. At that time it was discovered that all 100 diode elements had changed significantly in their electrical characteristics and were exhibiting unacceptably high leakage currents (μa instead of na) in the reversed bias mode. When voltage vs current measurements were made it appeared that the devices were behaving in a manner more like an FET channel than a diode. Hence, we labeled the defect as "channeling" of the diode array. Although we initially suspected heat during digicon processing as the damage mechanism, tests conducted with a like part showed this was not the cause. Contamination during processing was next suspected. The tube was then cut open so that the array could be examined directly. Measurements made with the scanning electron microscope and its energy dispersive x-ray spectrometer found traces of many contaminants on some of the elements but no contaminant that was universally present. The array was then heated to remove it from the ceramic header assembly and then broken into a number of pieces. One piece was sent out for Auger electron spectrometry and another piece subjected to electron microprobe analysis. Neither of these analyses found any unusual or unexplainable species. At this time we remeasured the electrical characteristics of the remaining portion of the diode array in the hope of pinpointing the leakage sites on the array surface. It was found instead that the diode characteristics were as good as they were prior to the tube processing. Isolation was better than 1000 megohm, breakdown was typically 50 volts and leakage currents were less than 20 na for all elements with no

"channeling." These facts strongly suggested that the contaminant was a high vapor pressure material that had volatilized when the array was heated to remove it from the header. This also explained the negative Auger and electron microprobe analyses. A series of tests and measurements were then made to determine at what point in the tube processing the contamination occurred. Although we were not successful in defining the contaminant species, or when it was introduced, we did recommend changes to the tube processing which would first inhibit the deposition of contaminant on the array and second remove any contaminant that may have deposited. As a further precaution, a 1200 Å silicon oxide passivation layer was added to the diode after assembly. The next batch of digicons successfully incorporated these changes and a change in sealing the header flange. These were used in the first three ultraviolet photometers which were flown late last year (Nov. 77).

When these digicons were processed, chemically cleaned copper "witness" samples were present in the chamber. One of these was subjected to ion microprobe mass analysis. This showed the major surface deposits to be chromium, indium and cesium, apparently deposited in that order. The analysis did not positively identify any alloy or compound.

8. PERFORMANCE DATA

Figures 4 and 5 show a front view of a complete 10×10 proximity focused digicon and a side view of a complete 1×36 electrostatically focused digicon as developed for our use. Figure 6 shows a complete 10×10 diode array mounted on its header assembly.

8.1 Diode Performance

Diodes in the digicons installed in the first flight photometers met specifications before and after assembly into the tubes. Some dead pixels were allowed in the periphery of the field of view. For example, one 10×10 array (in a digicon) had no elements with leakage currents in excess of 1.3 na (at 7v bias). In fact, most of the elements were below 1.0 na. This characteristic is extremely important since it is a direct factor to noise in the detector. Capacitance ranged from approximately 17 to 27 picofarad over the 100 elements (20 pf was the design goal).

8.2 Photocathode Performance

In general, the digicon quantum efficiencies were somewhat below specification but were nevertheless satisfactory for use. Figure 7 shows the overall



Figure 4. Front View of Proximity-Focused Digicon

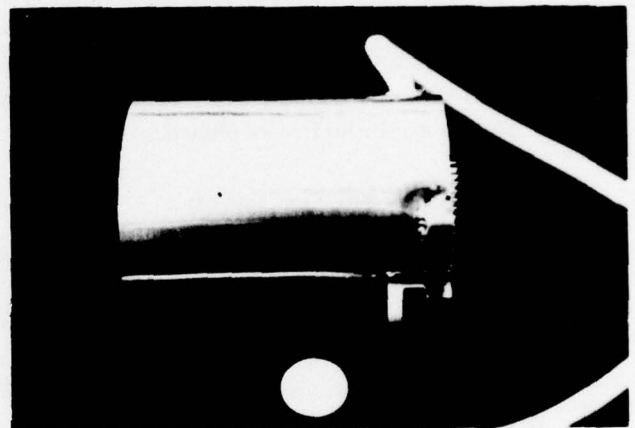


Figure 5. Side View of Electrostatically Focused Digicon

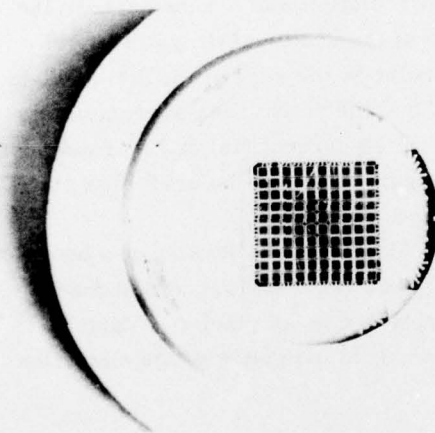


Figure 6. 10 x 10 Diode Array on Header Assembly

quantum efficiency for one of the detectors flown last year. It had a cesium iodide photocathode on a magnesium fluoride window.

8.3 Pulse Height Distributions

Figure 8 shows pulse height distributions at 25 kV bias from the first three proximity focused digicons installed in the flight ultraviolet photometers. The sharply defined photoelectron peak characteristic of digicons is apparent in all three photos. In fact, detectable peaks could be obtained at biases as low as 15-17 kV. In the first photo, the peak occurs at 22.5 Kev indicating a 2.5 Kev loss in the diode-dead layers (passivated and aluminized). The second digicon had an even more sharply defined peak (FWHM = 6.9 Kev, but still broader than the design goal) which occurred at 23.9 Kev. The third digicon showed a photoelectron peak at 22.2 Kev atop a FWHM of 8.2 Kev. Visible in the last two photos is evidence of a small peak at about twice the photoelectron peak, apparently due to statistical coincidence.

8.4 Dynamic Range and Linearity

Figure 9 shows the relationship between count rate and input flux for the digicon and its associated signal processing electronics of Figure 8b. The requirement of linearity to 5×10^4 c/s was not met. The data shows significant departure from linearity about 2.5×10^4 . Nevertheless, it appears possible to use the detector/electronics subsystem to rates approaching 10^5 counts per second with appropriate correction for nonlinearity.

8.5 Pixel to Pixel Response and Distortions

Figure 10 shows the response of a line of diode pixels in one of the first flight photometers. A collimated beam of ultraviolet radiation was scanned across the photometer field of view. Normal incidence is at the center of the gap between pixels 47 and 57. Considering the half power point as the edge of the active diode region, then the gaps are approximately 0.02° and the active area approximately 0.40° . The uniformity of pixel response is about 10 percent (1σ) and a pronounced electron optical distortion can be seen in the angular width of the near edge pixels (17 and 87) as compared to the center pixels (47 and 57).

Additional distortion can be seen in Figure 11 obtained by looking at a homogeneous background (lyman alpha geocorona). The dark spots are either dead pixels or optically obscured corners. Light spots are noisy pixels. A faint "barrel" distortion is visible in the original plot again indicative of the distortion in the proximity focused detector.

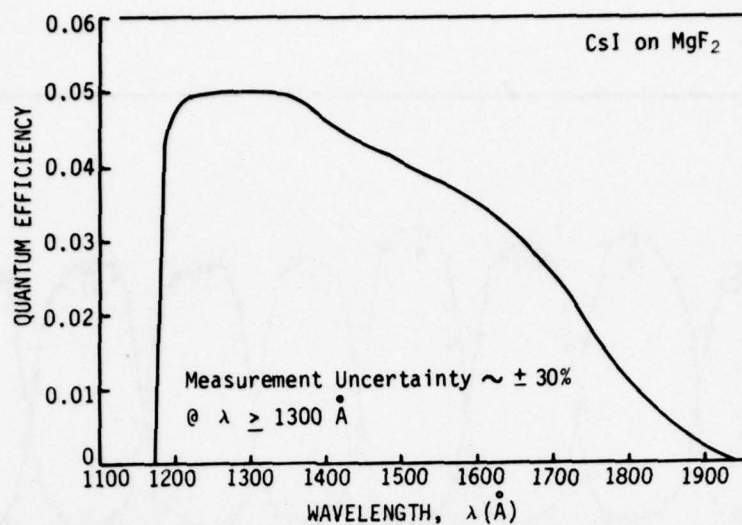


Figure 7. Vacuum Ultraviolet Photometer Detector Quantum Efficiency

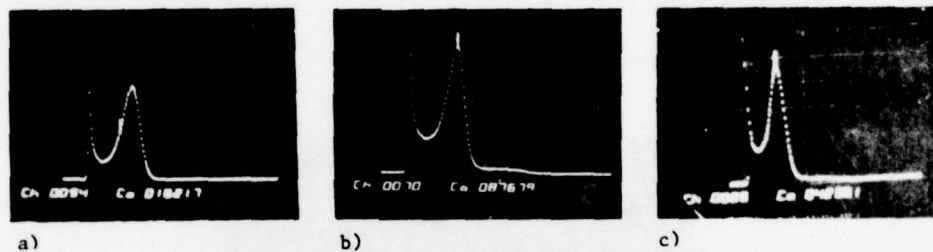


Figure 8. Pulse Height Distribution at 25 kV Input Bias. (a) digicon 10-13; (b) digicon 10-14; and (c) digicon 10-15

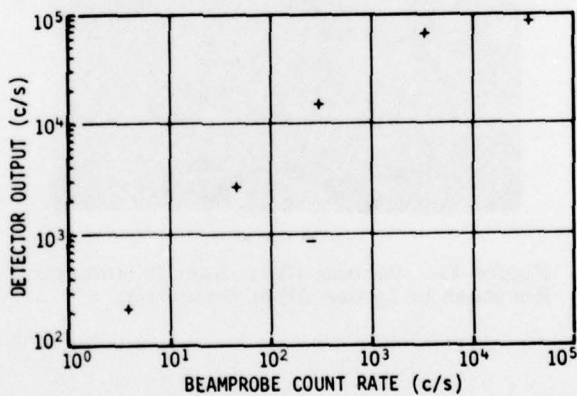


Figure 9. Vacuum Ultraviolet Photometer Detector Count Rate vs Input Flux

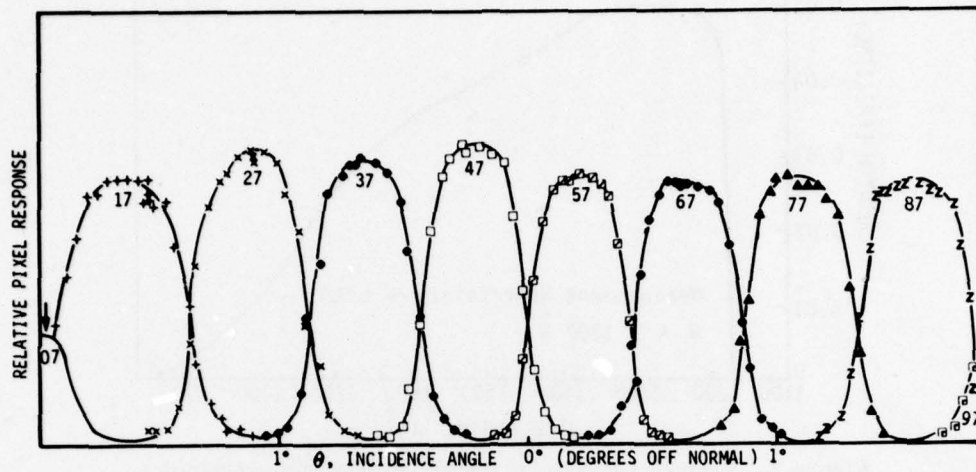


Figure 10. Vacuum Ultraviolet Photometer Detector Array Scan

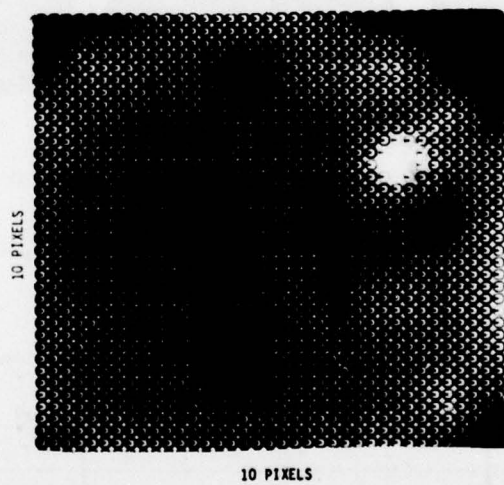


Figure 11. Vacuum Ultraviolet Photometer Response to Lyman Alpha Geocorona

9. SUMMARY

Two special digicon configurations were developed for use in a series of ultraviolet photometers and spectrometers for rocket flight. Development difficulties emphasized the great care required to successfully process silicon semiconductors in vacuum tubes, and in designing for high voltage operation. These difficulties were no doubt intensified by the small size of one of the detectors. Following resolution of the design and fabrication difficulties, the digicon, although it did not meet all of the original performance specifications, was shown through the formal environmental test program conducted on the instruments and by the subsequent rocket flight to be a satisfactory sensor for use in space. This program also helped demonstrate that the digicon would be a satisfactory sensor for use in the two spectrographs to be flown in the Space Telescope. It should be noted that the digicons in the second set of ultraviolet photometers are exhibiting dark counts as low as 0.03 per second per element at room temperature.

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